On Optimizing the Configuration of Time-Transfer Links Used to Generate TAI

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Recent work on the uncertainties of [*UTC*-*UTC*(*k*)] has made it possible to quantify the effects of different configurations of the time-transfer links used to generate International Atomic Time (TAI). The optimal topology depends upon the magnitude and character of the time-transfer noise of the relevant systems, the correlations between the time-transfer links, the required degree of robustness, the operational practices and equipment at pivot and crossover sites, and the operational complexity of generating TAI on a routine basis. The authors are members of a study group of the Consultative Committee for Time and Frequency (CCTF) Working Group on TAI that is studying these issues, and this paper will present considerations relevant to the problem.

I. INTRODUCTION

Time transfer for the generation of International Atomic Time (TAI) is achieved by a variety of techniques, including single-channel and multi-channel GPS Common View (CV), dual-frequency P-Code GPS data from geodetic receivers (P3), Ku-band Two Way Satellite Time and Frequency Transfer (TWSTFT), and X-band TWSTFT [1]. In order to improve TAI-generation, the BIPM Time Section has asked the CCTF to study certain proposals. One involved replacing CV time transfer by GPS All-in-View (AV) [2-4] time transfer. The difference is minimal on short links. Long-distance links would benefit through the greater number of observations and the more equal distribution of satellite observation angles, at the price of sensitivity to the corrected time of the satellites.

This paper is presented by a study group of the Working Group on TAI to analyze possible means of combining the set of available time-transfer links to reduce the uncertainties in and increase the robustness of the creation of TAI. The existing theory is described, the utility of using redundant links is discussed, and the importance of monitoring hardware at crossover sites is developed.

II. THEORY OF TIME TRANSFER UNCERTAINTIES

The theory described in this section has recently been developed for numerical computation of the uncertainty of the difference [*UTC*-*UTC*(*k*)] between Coordinated Universal Time (UTC) and its realization by any laboratory k, UTC(k) [5-7].

UTC is generated by adding leap seconds to TAI. TAI is generated by steering the Free Atomic Timescale (Echelle Atomique Libre, EAL) to a weighted average of the frequencies of primary frequency standards so that the TAI second will realize the SI second. EAL is created by averaging clock data from participating laboratories, whose times are differenced via the several time-transfer links. TAI and EAL are currently created using the minimum necessary number of time transfer links between laboratories. One significant element in the uncertainty analysis is the distinction between link-based uncertainties and site-based uncertainties (Figure 1). Site-based uncertainties depend only on the site and contribute equally to all links involving the site. Link-based uncertainties are a property of the pair of sites that make up the link. They cannot be estimated from separately-computed uncertainties of each site. The total uncertainty of any link is assumed to be the quadratic sum of the link-based

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uncertainty and the two laboratories' site-based uncertainties.

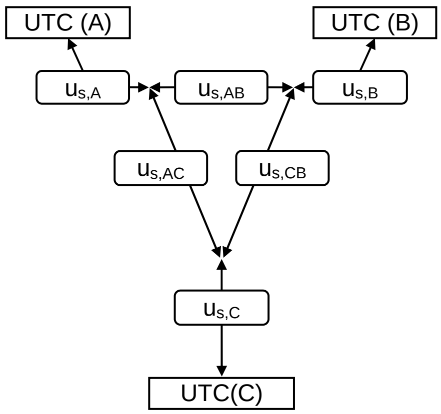

Figure 1. Site-based uncertainties ($U_{s,X}$) and link-based uncertainties ($U_{s,XY}$).

In a network dominated by site-based noise, it makes no difference which links are used to create the non-redundant set. In the example shown in Figure 1, the time transfer between any two sites or clocks A and B is written A-B. Time transfer between A and B achieved by links with C would be written as (A-C) + (C-B). If all uncertainties associated with C are site-based, then A-B is independent of C. Also, the closure of the three signed pair-differences between any three systems, (A-C)+(C-B)+(B-A), is zero. Hence, averaging redundant links would have no effect and TAI would be independent of the topology of any network dominated by site-based noise.

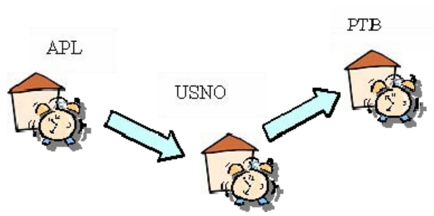

Figure 2. Example in which the USNO is a crossover site if the APL-USNO link is via GPS and the USNO-PTB link is via TWSTFT.

In contrast, link-based noise contributes to the uncertainties between all pairs of laboratories that include the link in the chain of timing links between them. If link-based noise was not negligible compared to site-based noise, the numerical computation of EAL would be topology-dependent. The weight of the primary standards used to measure the frequency difference between TAI and the SI second would also be topology-dependent. Numerical computations show that a system dominated by an equal amount of site-based noise in all links has 50% smaller uncertainties than one dominated by an equal amount of noise per link, but which is link-based [7]. The effects of link-based noise would be reduced by averaging redundant links, and this is investigated below.

The uncertainties of GPS observations are largely site-based because antenna, receiver, and signal-path delays depend only on the satellite in view, the laboratory receiver system, and their geometric relationship. In CV, however, link-based uncertainties are generated through link-dependent sampling in time and observation direction. In unfiltered AV link-based noise is nonexistent because the time and satellite direction samplings do not depend on the link. Link- based noise can exist in filtered AV, if the BIPM applies Vondrak smoothing after generating AV differences between two sites. This can be observed through nonzero closures [8].

The uncertainties of TWSTFT are largely site-based and typically attributed to uncalibrated long-term delay variations in the full signal path. However, some link-dependent effects come into play. Systematic effects are due to the slightly different frequencies used in some links, the slightly different spread-spectrum codes in the links, the link-dependent character of the calibrations, and multiplicative bandpass effects. The latter is due to the overall instrumental delay being the average of the delays at each frequency, weighted by the product of the amplitudes of the two system bandpasses. Link-dependent noise is also introduced from equipment and timescale instabilities between observations.

Of particular interest for TAI-generation are “crossover sites”, which are pivot sites that involve links using different techniques or different equipment. Because the uncertainties in TWSTFT and GPS are completely uncorrelated, at crossover sites even a system dominated by site-based uncertainties acts as if the uncertainties were link-based. In a hybrid situation in which a TWSTFT link is calibrated by GPS, the crossover properties would apply only to the uncertainties that do not involve the calibration.

The topologies used by the BIPM involve a minimum number of pivots, all of which are currently crossover sites. Numerical simulations using the tools developed for references [5-7] have confirmed that such topologies can minimize the overall effect of link-based noise. For example, assume that all TWSTFT observations have link-based uncertainties of 400 ps. In this case the USNO-PTB TWSTFT link could be replaced by a USNO-NPL TWSTFT link, which would act in conjunction with the NPL-PTB TWSTFT link already in use. But this would add the NPL-PTB link's 400 ps uncertainty to every link between the USNO and the European, Asian, Australian, and American laboratories linked to the USNO via NPL. This includes almost every other laboratory, and would raise the uncertainty of [*UTC-UTC*(*USNO*)] due to statistical (type A) errors by 25%, and those of other laboratories by 5-10%.

III. THE CROSSOVER SITES

Although interesting studies of the benefits of averaging different modes of time transfer data are underway [9], in practice the BIPM has followed a strategy of shifting from GPS links to more precise and accurate TWSTFT links. Should the BIPM switch to the AV methodology, link-based noise will virtually disappear from all GPS links. At the crossover sites, however, all site-based GPS and TWSTFT uncertainties, noise, and uncalibrated delay variations will act as if link-based. For this reason the ideal crossover site would have at least two TWSTFT and GPS systems so that instrumental effects can be identified and removed. Traceability to a site maser would be needed so as to have the ability to relate observations made at different times should it be necessary. The environmental effect on observations should be minimized through environmentally insensitive components, with minimal exposure to exterior or even room temperature variations. Multipath due to reflections from exterior structures and to reflections within cables should be minimized. All key components should be monitored electronically and through human oversight. An automated warning system will allow rapid correction of problems, while a postprocessed analysis will ensure data quality.

The current configuration of time links used for TAI (Figure 3) includes four crossover sites: NICT, NIST, PTB, and USNO, with most of the links going to PTB or NICT. To optimize the precision and accuracy of the configuration, it is best to minimize the number of crossover sites, because each one contributes link-based errors that affect all time transfer between laboratories on one side of the site and those on the other side. If one were to measure the overall sensitivity to biases at crossover sites by the product of the weighted number of clocks on each side and the sensitivity of their UTC-measurement to a bias at the crossover site, then one can show that it is almost always better to have fewer crossover sites. It is better to have multiple GPS receivers at any crossover site, if an average bias can be determined by zero baseline CV between the GPS receivers.

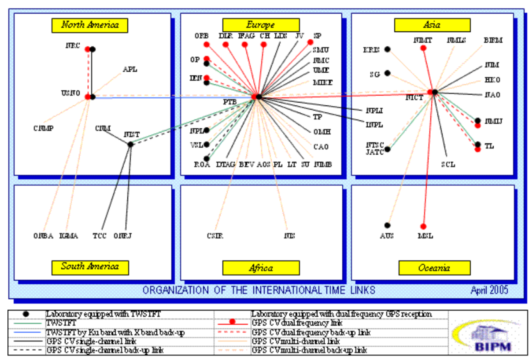

Figure 3. Links used in April, 2005 by the BIPM to generate EAL, and with it TAI and UTC.

In the case of GPS time-transfer via AV the concept of averaging collocated receivers at crossover sites can be extended to a global average over all or most sites that have operational TWSTFT and GPS systems. This averaging can be realized in the form of a least-squares fit to determine one bias parameter per crossover site, with an overall average bias constrained to be zero. The solution to that fit yields extra link calibrations for input into the BIPM's software package used to generate EAL and therefore TAI. Alternately, this fit can be used to monitor the delay variations at the crossover site. A simulation assuming TWSTFT data have 300 ps of link-based noise and that GPS has 100 ps of link-based noise plus 1.0 ns of site-based noise at five TWSTFT and GPS-enabled sites indicated that any bias variation at the crossover site can be identified to within

80 ps. The magnitude of the fitted bias is decreased by the contribution of the crossover site's simulated bias change to the average bias.

IV. USE OF REDUNDANT TWSTFT LINKS

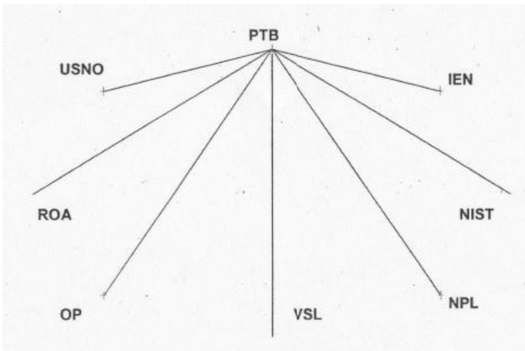

Figure 4. Non-redundant configuration of TWSTFT links in which PTB is the pivot.

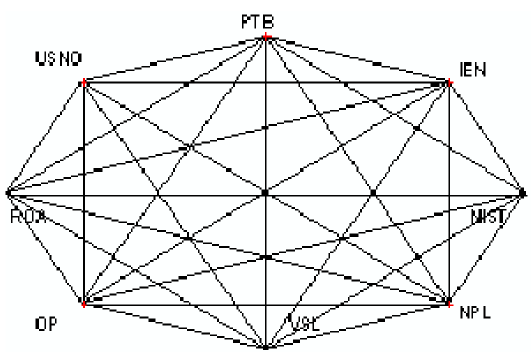

Figure 5. Complete set of European and American TWSTFT links available from sites contributing to previous figure.

It may be possible to improve TWSTFT time transfer through use of redundant links [10-11]. In order to study this, a trial least-squares fit was made using TWSTFT data, taken every 2 hours, from European and North American labs (Figures 4 and 5). The first step was to create a software calibration of all links not involving the reference laboratory, so that they would be consistent with the links between each laboratory and a reference laboratory. Once the calibrations were made consistent, the fits used as reference laboratory either the PTB (the current pivot used by the BIPM, whose time reference is the primary clock CS2 [12] or NPL whose time reference is a maser. These fits determined the time of each laboratory's master clock relative to the reference laboratory, weighting all links equally. No significant statistical reduction in the scatter of the master clock differences was noted between observations, even in the 2-hour intervals. The RMS difference between the actual link between each lab and the PTB differed from the fitted master clock difference between 100 and 400 ps. From this we conclude that no significant precision improvements can be expected from the simplest method of averaging redundant TWSTFT links. The robustness of the system would be improved through averaging, but only if the data inspection and integrity checking procedures were improved commensurately with the increased complexity. Figure 6 shows histograms of the difference between using the direct link to determine [*UTC*(*PTB*)-*UTC*(*k*)] and using the fit, for all October, 2005 data. Figure 7 shows the closure about all possible triplets of North American and European labs in 2005. The results are consistent with an overall link-based uncertainty of 300-400 ps for TWSTFT.

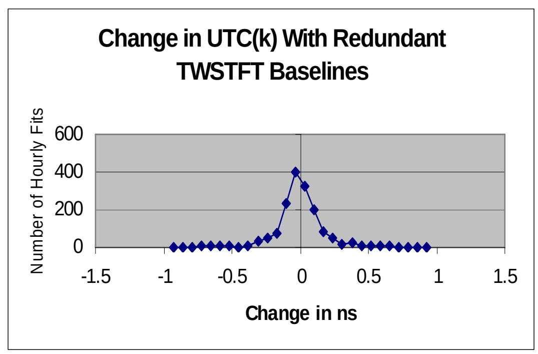

Figure 6. Histogram of differences in UTC(k) generated by including redundant links to TAI-generation. [*UTC*(*k*)-*UTC*(*PTB*) was computed for each hour using redundant links, and differenced with direct measurements.

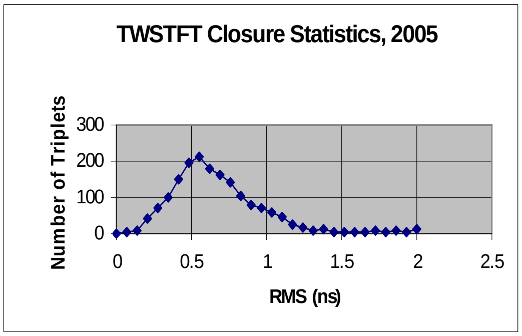

Figure 7. Histogram of hourly closures of available over all triplets of N. American and European labs. RMS was computed from algebraic sum of timing differences for each triplet, and is thus a measure of the link-based noise over the three links.

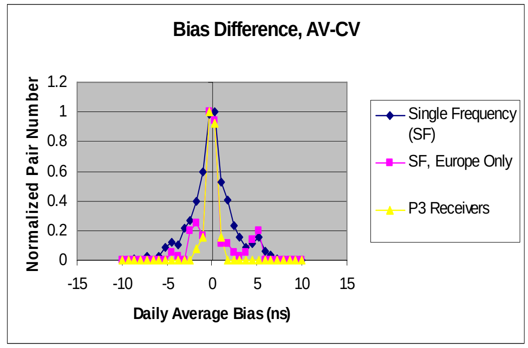

Figure 8. Histogram of daily bias between CV and AV techniques, over all laboratory pairs. differences reflect link-based effects with CV that are not present in AV.

V. USE OF REDUNDANT GPS LINKS

Because unfiltered AV has no link-based noise, no improvement could be expected from averaging redundant AV links. In order to study possible benefits from averaging redundant CV differences, ionosphere and orbit-corrected GPS time transfer data made publicly available by the BIPM were analyzed for the year 2005. Figures 8 and 9 show the biases and RMS differences between AV and CV for all pairs of laboratories. Figures 10 and 11 show analogous histograms of the CV closures among all triplets of laboratories.

Figures 12 and 13 show the average and RMS differences between daily averages of all GPS data taken towards one hemisphere at the site (east or north) and those data taken towards the opposite hemisphere (west or south). Also shown are the differences between all data taken above 30 degrees elevation and between 10 and 30 degrees elevation. These differences cause link-based effects in CV that are not present in AV. Note that northern observations tend to be low-elevation at higher latitudes.

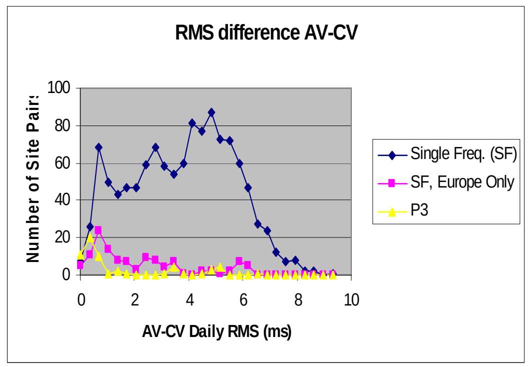

Figure 9. Histogram of RMS of daily difference between AV and CV techniques, over all laboratory pairs.

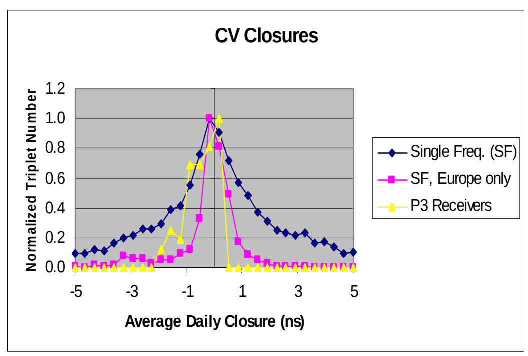

Figure 10. Histogram of bias of closure of daily CV reductions over all lab triplets. Plots are normalized for display.

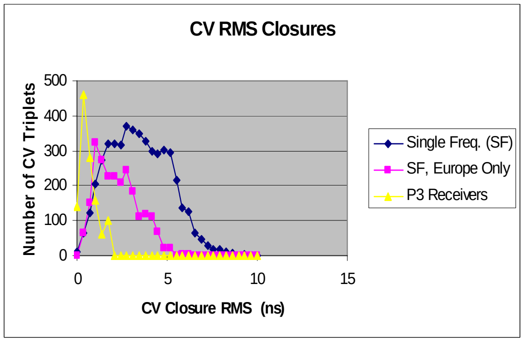

Figure 11. Histogram of RMS of closures of daily CV reductions over all lab triplets. For display, the number of European SF triplets is multiplied by 5, and of P3 triplets by 20.

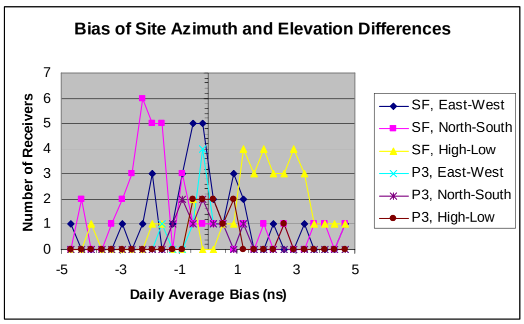

Figure 12. Histogram of difference between daily averages of all GPS observations at different elevations or opposing cardinal directions, for all labs.

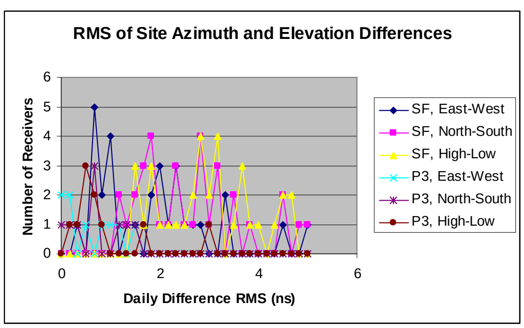

Figure 13. Histogram of RMS of daily difference between averages of all GPS observations at different elevations or opposing cardinal directions, for all sites.

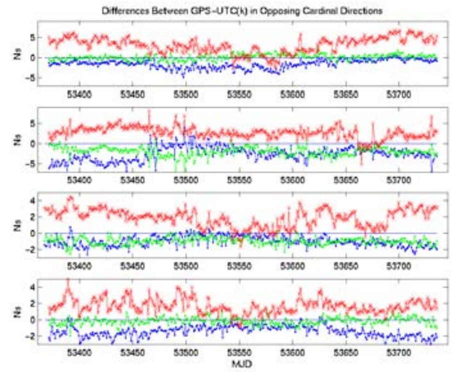

Figure 14. Differences between ionosphere and orbit-corrected single-frequency GPS observations at different elevations or in opposing cardinal directions, from the four crossover sites. Sites from top down are NICT, NIST, PTB, and USNO. North-south differences are shown by a blue dot, east-west differences by a green +, and hi-low elevation differences by a red x. Seasonal effects are apparent. Plots are not to same vertical scale.

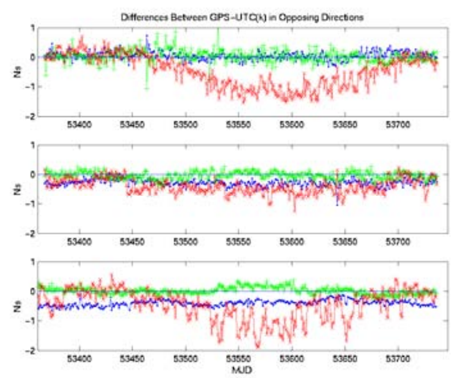

Figure 15. Hemispheric differences of orbit-corrected P3 data from three crossover sites. Sites from top down are NICT, PTB, and USNO, and otherwise as in previous figure.

Since the crossover sites are of particular concern, their hemisphere differences are plotted next. Seasonal effects are apparent, as is the higher quality of the P3 data.

For completeness, we also show how the receiver instrumental delay at the L1 frequency has varied between two receivers at each of the 3 crossover sites contributing to the P3 program.

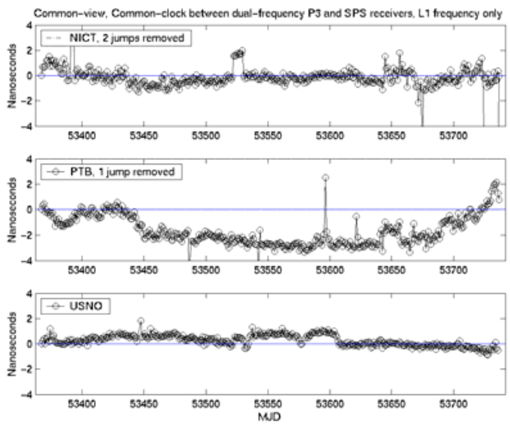

Figure 16. Differential delay variations between the single-frequency and the P3 receivers at 3 crossover sites. Data are common clock and show the variation at the L1 frequency only.

Figures 9-16 show a consistent pattern that CV results in calibration biases and daily scatters at the level of a few ns in single frequency receivers. Inter-European CV data are of higher quality because CV link-based noise increases in long baselines. In general, P3 data show less bias and RMS scatter than the single frequency (SF) receivers; this is likely due to better multipath rejection. However, the geodetic receivers used in the P3 experiment can show sudden calibration jumps at the ns level [13].

Should the BIPM continue using CV, redundant GPS links could be averaged and still conform to the current practices giving 100% weight to all TWSTFT links. A fit would determine the bias between TWSTFT and GPS systems at the crossover sites. It would use TWSTFT link data and all redundant links from those laboratories that do not do TWSTFT, under the constraint that the average bias parameter is zero.

Whether GPS time transfer is achieved by AV or CV, fits that average GPS with TWSTFT are possible. Such averages would also help detect outliers and identify calibration variations.

VI. CONCLUSIONS

The time-transfer links used to generate TAI could be improved through careful monitoring of the TWSTFT and GPS equipment at crossover sites, and analytically determining the bias between them. Use of redundant TWSTFT links may not improve precision, and use of redundant AV links would make minimal difference to precision or robustness. Combining different techniques could lead to still more improvements, but this has not been investigated.

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